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MOLECULAR EMISSION IN CHEMICALLY ACTIVE PROTOSTELLAR OUTFLOWS

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Abstract. Protostellar outflows play an important role in the dynamical and chemical evolution of cloud through shocks. The *Herschel Space Observatory* (HSO) brings new insight both on the molecular content and the physical conditions in protostellar shocks through high spectral and angular resolution studies of the emission of major gas cooling agents and hydrides. The Herschel/CHESS key-program is carrying out an in depth study of the prototypical shock region L1157-B1. Analysis of the line profiles detected allows to constrain the formation/destruction route of various molecular species, in relation with the predictions of MHD shock models. The Herschel/WISH key-program investigates the properties and origin of water emission in a broad sample of protostellar outflows and envelopes. Implications of the first results for future studies on mass-loss phenomena are discussed.

Keywords: ISM: astrochemistry, individual objects: L1157, ISM: molecules, ISM: jets, outflows, stars: formation

1 Introduction

Outflows are the most spectacular manifestation of the mass-loss phenomena which take place along the protostellar evolution, from the very early, embedded Class 0 to the late Class II phase, when the parental cocoon is dispersed. Three main types of mass-loss phenomena have been identified from their observational signatures : a) highly collimated jets of hot ($T > 1000\,\mathrm{K}$), partly ionized/atomic material, which propagate at velocities (typically several hundreds of $\mathrm{km\,s^{-1}}$), detected at optical and near-IR wavelengths; b) outflow cavities of cold (10 K) molecular gas, propagating at low-velocity ($\sim 10\,\mathrm{km\,s^{-1}}$), detected at millimeter wavelengths; c) bullets of molecular gas moving at extremely high-velocities (EHV), comparable to the optical jet, also detected at millimeter wavelengths. The presence of a protostellar wide-angle wind, which would accompany the launch of a highly-collimated jet remains debated. The outflow cavities and the EHV bullets are understood in the framework of the jet-driven bowshock model as the result of the shock interaction of the high-velocity jet powered by the newly-born star with the parental cloud.

There is now large observational evidence that indeed outflows play an important in the chemical evolution of the cloud. Abundance enhancements of several orders of magnitude have been reported for various molecular species, e.g. SiO, SO, and CH_3OH in "chemically active" outflows (see e.g. Bachiller et al. 2001). More recently, complex organic molecules have been reported in L1157 (Arce et al. 2008; Codella et al. 2009). The formation route of these species, either gas phase or dust grain chemistry, remains strongly debated. Large differences in molecular abundances are observed not only between sources at different evolutionary stages but also between regions of the same flow (e.g. B1 and B2, Fig. 1), that remain unexplained. The recent instrumental developments at millimeter wavelengths now permit to undertake outflow millimeter line surveys at a reasonable cost so to explore in a systematic way their molecular content.

An important point is to determine whether the shock accelerating the outflow is a purely hydrodynamical discontinuity ("J-type" shock), or a continuous, non-dissociative("C-type") shock with a magnetic precursor where ions are decoupled from the neutral fluid. Indeed, the physical and dynamical conditions implied by C- and J-type shocks are very different. C-shocks are predicted to play an important role in the gas chemical evolution through the temperature and density changes resulting from the activation of endothermic reactions, ionization, and dust sputtering in the ion-neutral drift zones.

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The study of the H_2 rovibrational line emission at near- and mid-IR wavelengths has proven very successful, and could bring indirect evidence for MHD shocks in protostellar outflows (see e.g. Cabrit et al. 2003). The limited spectral resolution prevents any detailed study of the shock dynamics, however. The great promise of the *HSO* was precisely to give access to the emission of the major gas cooling agents in the submillimeter and far-infrared domain, CO and H_2O, at an angular resolution comparable to that of the largest ground-based telescopes. The high-spectral resolution of the heterodyne instrument HIFI permits to study the dynamics and to reconstruct the thermal profile in the shocked gas. Thanks to its unprecedented sensitivity, *Herschel* permits to search for the presence of hydrides, which play an important role in the chemical networks and the synthesis of more complex molecules. By probing the whole CO ladder from $J_{up} = 4$ ($E_{up} = 55.3\,K$) up to $J_{up} = 45$ ($E_{up} = 5120\,K$), Herschel is expected to establish the link between the cold gas of the outflow cavities detected in the millimeter range and the hot shocked gas detected at near-infrared wavelengths.

2 Peering into the protostellar shock L1157-B1

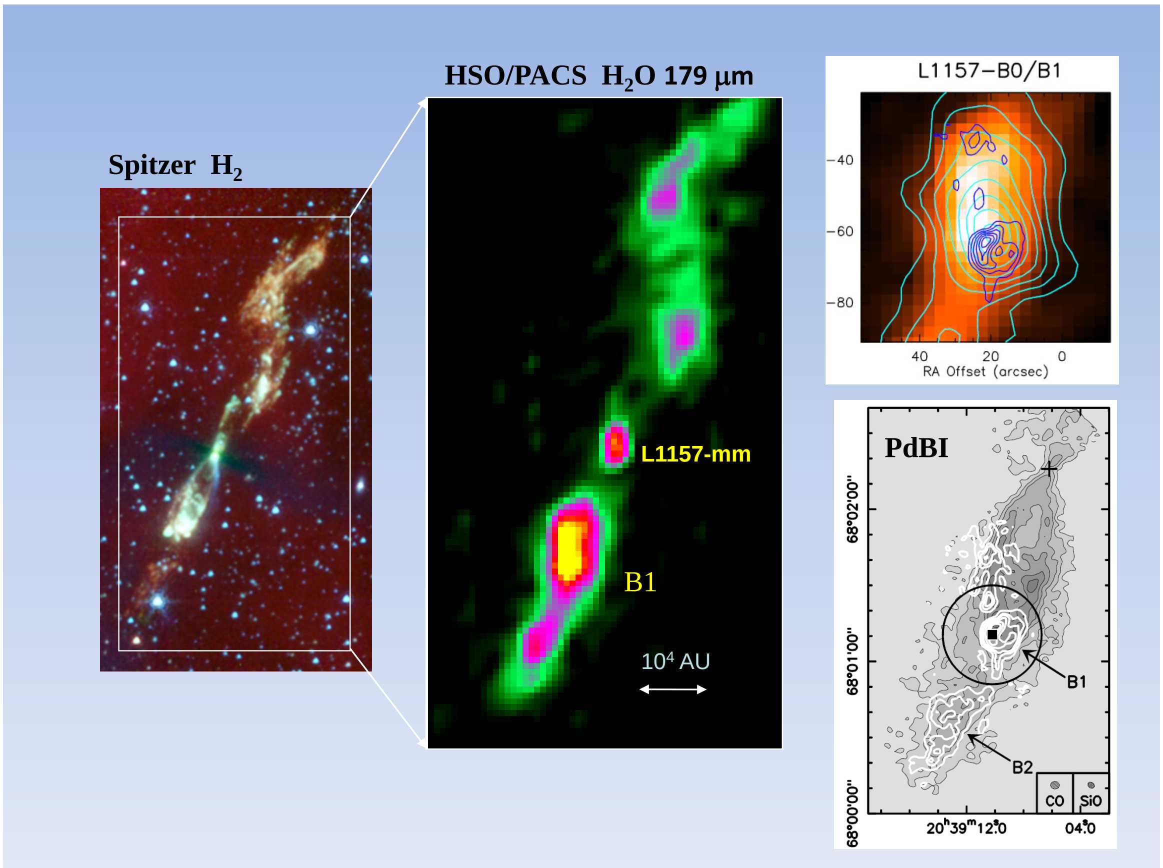

Fig. 1. Molecular gas emission the prototypical outflow L1157. *Left*: H_2 as seen with Spitzer/IRAC (Neufeld et al. 2009); *(middle)* H_2O $2_{12} - 1_{01}$ as seen with PACS (Nisini et al. 2010). *Bottom right:* CO 1-0 (greyscale) and SiO 2-1 (white contours) as seen with the PdBI (Gueth et al. 1996). *Top right:* Comparison of H_2O $2_{12} - 1_{01}$ (colorscale) and SiO 2-1 emissions at IRAM 30m and PdBI (light and dark blue contours, respectively) in the direction of B1.

The outflow from the Class 0 protostar IRAS20386+6751 ($L = 4 - 10\,L_\odot$) in the L1157 cloud (d= 440pc) is probably the best studied protostellar outflow at millimeter and far-infrared wavelengths (see Fig. 1; also Codella et al. 2009 and references therein). Mapping of the Southern lobe with the PdBI by Gueth et al. (1996) revealed two cavities associated with subsequent ejection episodes in the (precessing) protostellar jet. Bright millimeter line emission was detected at the position of the shocks B1 and B2, coinciding with the apex of the cavities (Fig. 1; Bachiller et al. 2001).

L1157-B1 was observed with the three instruments onboard *HSO* in the course of the guaranteed-time keyproject CHESS, dedicated to the exploration of molecular complexity in star-forming regions (Ceccarelli et al. 2010). A full spectrum was obtained in the submillimeter range ($672-192\mu m$) with SPIRE and in the far-infrared range ($55-200\mu m$) with PACS (Benedettini et al. 2011). The whole spectrum is dominated by the CO line emission (the transitions from $J_{up}=4$ up to $J_{up}=22$ were detected) and, to a lesser extent, by a few lines of H_2O OH and OI. Estimating the luminosity of these various tracers, it comes out that the gas cooling is dominated by H_2 and CO.

About 20 molecular species were identified from the CHESS survey (Codella et al. 2010; Lefloch et al. 2011 in prep). A few hydrides were detected for the time in outflows, like HCl (Codella et al. 2011). The analysis of the molecular line profiles shows that the emission arises from two physically distinct regions (Figs. 1-2; also Lefloch et al. 2010) : a compact ($\sim 7''$), CO and H_2O rich region, of high-excitation, emitting at high-velocity (HVC); an extended ($\sim 20''$), molecular-rich region (LVC), of lower excitation, emitting at low-velocity. This is illustrated by the comparison of the profiles of the CO transitions from $\mathrm{J_{up}}=5$ up to $\mathrm{J_{up}}=13$ in Fig. 2, which have been scaled so to match the emission in the high-velocity gas (HVC). One observes a decrease of the CO line intensity in the low-velocity range (LVC) as a function of J_{up}. There is an excellent agreement between the profiles of the high-J CO lines ($J_{up}\geq 13$ and $\mathrm{E_{up}}>500\,\mathrm{K}$) and the SiO line arising from the HVC, as mapped at the PdBI (Fig. 2). This implies that these tracers are probing the same region of the shock. The physical conditions in the HVC were obtained from a simple modelling of the CO spectral distribution in the Large-Velocity Gradient approach. The complementarity of PACS and HIFI is essential in this kind of analysis : the fit to the whole data set favors gas temperatures ($\sim 600\,\mathrm{K}$) and densities $n(\mathrm{H_2})\simeq 10^5\,\mathrm{cm^{-3}}$. The CO flux distribution of the high-velocity component (filled circles and triangles in the top right panel in Fig. 2) is well accounted for by a J-type shock propagating into gas of density $n(\mathrm{H_2})\simeq 10^4\,\mathrm{cm^{-3}}$ with a shock velocity $V_s\simeq 10\,\mathrm{km\,s^{-1}}$. Interestingly, the CO flux distribution of the LVC (empty triangles in the top right panel in Fig. 2) is well accounted for by a steady-state magnetized (C-type) shock.

The high spectral resolution of HIFI permits to derive both the physical *and* chemical structure of the shock region from the molecular line profiles. The ratio of the H_2O $1_{10}-1_{01}$ to CO 5-4 line intensity shows a continuous increase as a function of velocity, consistent with an increase of the H_2O abundance in the higher-excitation gas of the HVC in the shock. Lefloch et al. (2010) estimated an increase of one to two orders of magnitude in the H_2O abundance between the LVC and the HVC. A similar behaviour was observed between water and NH_3 (Fig. 2). Unlike NH_3 which is produced only from dust grain chemistry, H_2O can form very efficiently in the gas phase, as soon as $\mathrm{T_{kin}}$ exceeds 220 K. Viti et al. (2011) argue that the increase of the H_2O/NH_3 intensity ratio actually reflects the destruction of NH_3 in the gas phase, via the reaction $NH_3 + H \rightarrow NH_2 + H_2$, which has an energy barrier of 4000 K. The authors' modelling shows that this reaction is activated when T_{kin} reaches about 3500 K in the gas, which, then, allows them to constrain the density and velocity of the shock. Observations of other shock regions have just been completed with Herschel and should allow to test the suggestion of Viti et al. over a wide range of shock parameters.

The H_2O $2_{12}-1_{01}$ line at $179\mu m$ was mapped with PACS in the WISH program (Fig. 1). The H_2O emission is spatially correlated with that of the H_2 pure rotational lines (Fig. 1; Neufeld et al. 2009), and corresponds well with the peaks of other shock-produced molecules such as SiO and NH_3 along the walls of the outflow cavity, where low-velocity shocks are observed (see Fig. 1, top right panel). In contrast with these species, H_2O is also strong at the source position itself. The analysis of the $H_2O179\mu m$ emission line, combined with existing Odin and SWAS data, shows that water originates in warm compact shocked clumps of few arcsec in size, where the water abundance is of the order of 10^{-4}, i.e., close to that expected from high-temperature chemistry.

3 Water in Protostellar Outflows

The importance of water as a physical diagnostic stems from the orders of magnitude variations in its gas phase abundance between warm and cold regions. Although thermal lines of H_2O cannot be observed from ground, a few masing lines are however accessible under "dry" atmospheric conditions. The p-H_2O $3_{13}-2_{20}$ line at 183.3 GHz is especially interesting as it arises from a level rather low in energy ($\mathrm{E_{up}}\simeq 205\,\mathrm{K}$). The difficulties of these observations are such* that only few protostellar sources have been surveyed up to know.

Cepe E is an intermediate-mass Class 0 protostar of luminosity $\mathrm{L}\sim 75\,L_{\odot}$ where the p-H_2O $3_{13}-2_{20}$ was recently detected (Fig. 3; Lefloch et al. 2011). Emission was detected in the direction of the protostar only. Like in L1157-B1, one observes a strong similarity between the line profiles of SiO 2-1, as observed with the PdBI, and

*the atmospheric opacity can vary a lot on short timescales.

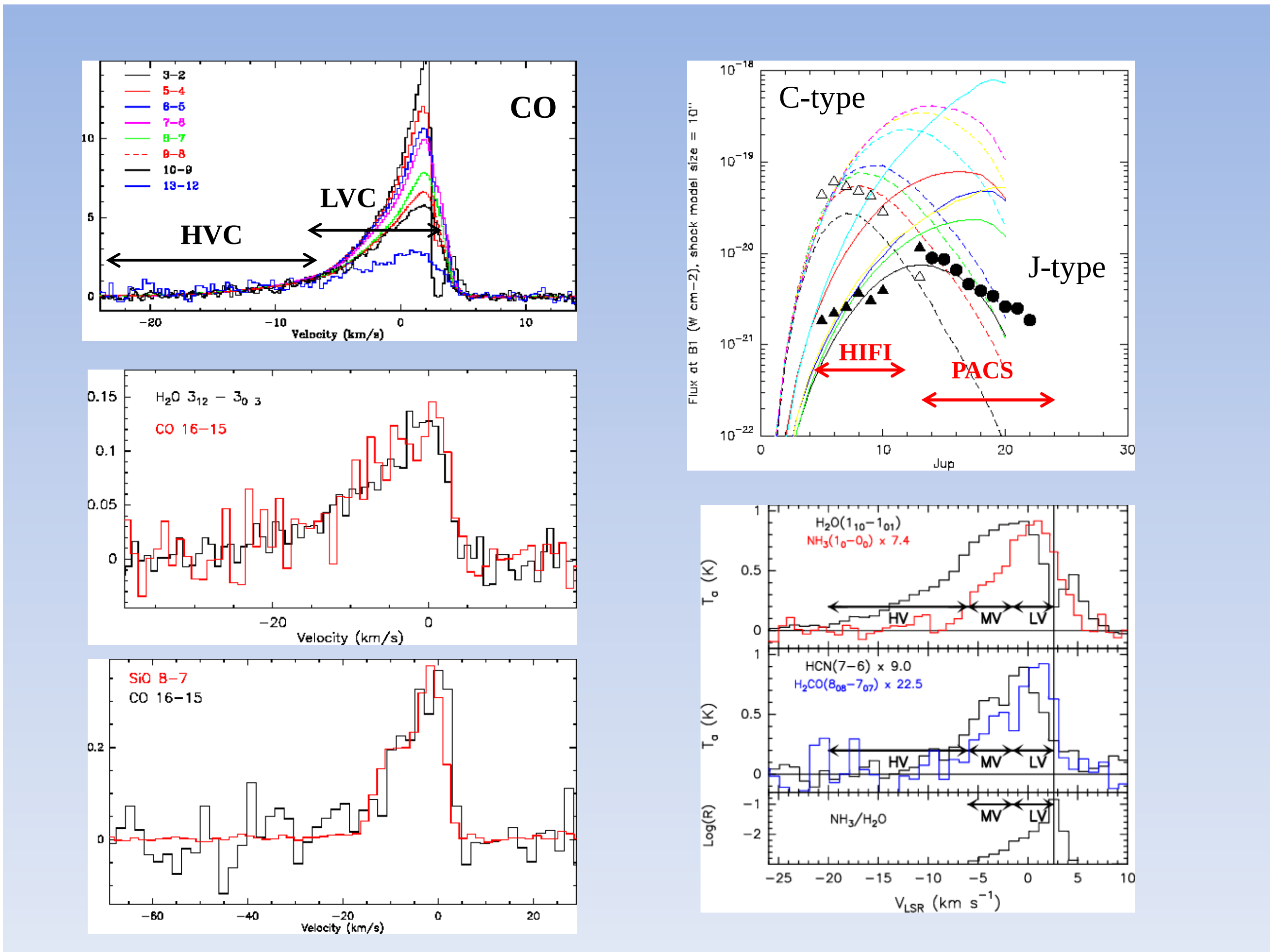

Fig. 2. Left: CO line emission detected with HIFI towards L1157-B1 (top;); comparison with shock tracers SiO 8-7 (bottom) and H_2O $3_{12} - 3_{03}$ (middle). (Lefloch et al. 2011, in prep). **Top right**: Comparison of the HVC CO fluxes obtained with PACS and HIFI with steady-state J-type (C-type) shock models in solid (dashed) contours (see Lefloch et al. 2011; Flower & Pineau des Forets 2010). **Bottom right**: ground-state transition of o-H_2O 557 GHz, NH_3, HCN(7-6) and H_2CO line profile observed in the same spectral band (Codella et al. 2010).

H_2O. Comparison with the SiO interferometric maps shows that the H_2O emission arises from high-velocity clumps (size $\sim 10^3$AU) of dense ($n \sim 10^6\,cm^{-3}$) and hot ($T \sim 200\,K$) gas, with a mass of a few $10^{-4}\,M_\odot$, probably tracing internal shocks in the jet. The water abundance derived ($\sim 10^{-4}$) is indeed consistent with that expected from gas phase chemistry. No emission was detected from the hot corino region itself.

The nature and the physical conditions of the H_2O emission in protostellar environments is one of the main goals of the WISH key-program (van Dishoeck et al. 2011). Observation of the ground state transition of o-H_2O $1_{10} - 1_{01}$ at 557 GHz towards a large sample of protostars shows that the emission is dominated by the emission of the outflow, from the early Class 0 to the Class I (Kristensen et al. 2010). The emission reaches velocities up to $40 - 50\,km\,s^{-1}$, although the line is somewhat narrower for evolved sources. The derived abundances are typically $\sim 10^{-4}$. In the chemically active outflow L1448-mm, Herschel/HIFI detected the presence of water bullets, similar to those detected in Cep E with the IRAM 30m, which appear to have formed from atomic oxygen in the high-velocity jet (Kristensen et al. 2011). Interestingly, determination of the water abundance in the inner protostellar envelope from $H_2^{18}O$ line observations yields values of a few $\sim 10^{-6}$, well below the 10^{-4} measured in outflows (Visser et al., in prep).

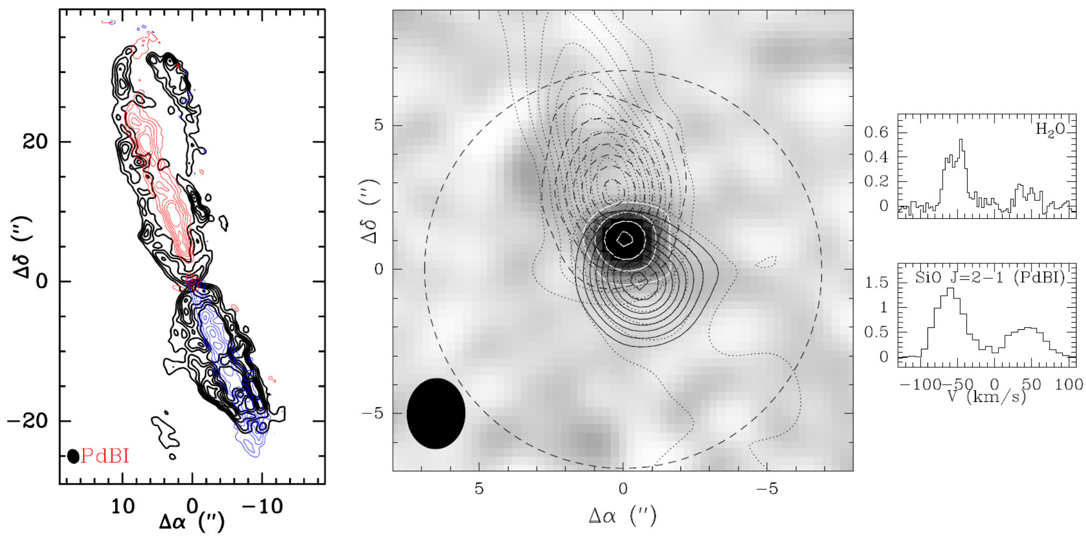

Fig. 3. Left: CO 2-1 emission in the Cep E protostellar outflow (black contours) and jet (red/blue contours). *(middle)* SiO 2-1 emission map as observed with the PdBI at 2" resolution. The jet emission is drawn in thin dotted contours; the SiO 2-1 emission integrated in the velocity range of H_2O emission is drawn in thick contours; the IRAM 30m beam at 183 GHz is drawn in dashed. **Right**: Comparison of the average SiO 2-1 (PdBI) and H_2O (IRAM 30m) line profiles observed towards the core (Lefloch et al. 2011).

4 Conclusions

The studies on H_2O line emission with Herschel and ground based telescopes have clearly established the importance of outflows and shocks in the chemical evolution of molecular clouds *and* protostellar envelopes. Systematic studies on the archetypal shock region L1157-B1 suggest that H_2O and other shock tracers like e.g. SiO actually display a very similar behaviour, an important result which should be established on a large source sample. Analysis of the molecular line emission detected with Herschel gives access to the structure of the shock region L1157-B1 with unprecedented detail, and in a rather consistent way despite the complexity of the region itself. A relatively simple picture emerges, with evidence for two shocks : a C-type shock, associated with the low-velocity, low-excitation gas in the wings of the bow, and a J-type, located close to the apex of the outflow cavity. The observational evidence for strong outflow shocks and efficient water production in the inner protostellar region opens new perspectives on the chemical complexity observed in these regions, attributed up to now to the evaporation of the ice mantles in the hot corino region, as a consequence of heating by the accretion luminosity. The characterization of these shocks should permit to better understand the origin of molecules in protostellar jets, and to discriminate between the various jet launch mechanisms, which will remain out of reach even to the next generation of millimeter interferometers (ALMA, NOEMA).

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